CALIFORNIA
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PowerTherm^{TM}: A Photovoltaic-Thermal Hybrid Commercial Roofing System

CONSULTANT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Photovoltaic-Thermal Hybrid Commercial Roofing System project, #500-97-045F conducted by PowerGuard California. The report is entitled PowerTherm: Photovoltaic-Thermal Hybrid Commercial Roofing System. This project contributes to the PIER Renewable Energy program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

PowerLight Corporation (PowerLight) has completed its PIER contract, "PowerTherm™ A Photovoltaic – Thermal Hybrid Commercial Roofing System." The overall goal of this project was to design and create a hybrid photovoltaic/thermal (PV/T) system, called PowerTherm™. This technological development will increase the economic value of PV roof-tile systems for building owners by providing them with two ways to lower their energy utility costs: photovoltaic electrical generation and solar water heating.

Objectives

This project addresses two PIER Program objectives: 1.) to improve the reliability of California's electricity system by developing a distributed-energy technology; and 2.) to reduce environmental risks from California's electric system by developing a deployable renewable energy source, which does not emit NOx (nitrous oxides), SOx (sulfur oxides), and CO2 (carbon dioxide) when generating electricity.

In developing a cost-effective PV/T rooftop system with superior qualities and performance to currently available products, PowerLight sought to

- Improve the overall system efficiency and performance, and
- Develop an economically viable product with a low installation cost and a short payback period.

The overall technical objective was to design, fabricate, and test this new product. PowerLight's specific technical objectives were to:

- Improve heat transfer between the PV laminate and solar-thermal absorber by 40%;
- Increase the effective irradiance of the sloped collector by 5%;
- Increase the thermal performance of the overall system by 35%;
- Improve the overall system efficiency by 45%.

The overall economic/cost objective of the project was to introduce a cost-effective PowerTherm™ product to commercial and residential building owners. The specific economic objectives were to:

- Achieve a net (thermal only) system production tile cost of $6 per square foot;
- Achieve a thermal component payback of less than 5 years in potential target markets.

Outcomes

Through the generosity of the California Energy Commission, and the PIER Program, PowerLight was able to realize the following significant achievements during the development of PowerTherm.

- Identified lucrative target markets for PowerTherm: through extensive market analysis and a thorough assessment of product capabilities, commercial and residential pool heating applications in Hawaii and California were identified as ideal near-term markets for this product;

- Created initial product concept: by leveraging the successful product development and manufacture of PowerLight's flagship product, PowerGuard©, PowerLight quickly initiated development and testing of its first PV/T product concept;
- Developed a unique product concept: through design iteration, materials research, testing, and development of supplier relationships, PowerLight created a unique, high quality product which uses inexpensive flexible thin film technology bonded to commercially available unglazed solar thermal collectors;
- Developed advanced manufacturing and fabrication techniques: improvements in the manufacturing process were made by reducing both cost and cycle time. Design and development of unique lamination equipment and materials led to significant progress toward product commercialization;
- Deployed six working systems: these systems were installed and monitored at two sites in California and one in Hawaii for testing and performance verification purposes;
- Researched applicable certifications needed for commercialization: these included ICBO, International Electrotechnical Commission (IEC), and UL certifications. UL conducted a design review of PowerTherm;
- Developed business and marketing strategies: PowerLight developed a finance packaging plan, identified and built alliances with key industry partners, and developed installation, operation, and maintenance plans for the product;
- Developed equipment that can be used both for production and further research;
- Optimized critical manufacturing process parameters: through iterative testing and trial manufacturing runs, these parameters were adjusted in order to achieve high quality product parts;
- Produced full-sized prototypes (Figure 1) for certification and field-testing purposes: demonstration systems were installed to monitor performance and reliability. In addition, a full sized system has been sent to FSEC for evaluation.

Conclusions, Recommendations, and Benefits to California

The result of this work is the development of a PV/T product with an installed cost that is 25% less than the cost of two separate systems, and has half the footprint. This successful PIER project has made possible the development of a viable commercial product that will offer Californians and others a cost-effective, environmentally conscious energy generation alternative. With further manufacturing improvements, advanced testing and validation through demonstration and test units, and focused market development, PowerTherm can be successfully deployed in target markets such as California and Hawaii.

Figure 1: Example of pool heating application for solar thermal collectors

Abstract

PowerLight Corporation (PowerLight) has completed its PIER contract, "PowerTherm™ A Photovoltaic – Thermal Hybrid Commercial Roofing System." The overall goal of this project was to design and create a hybrid photovoltaic/thermal (PV/T) system, called PowerTherm™. This document is the final report for this contract.

Through the generosity of the California Engineering Commission, which made this PIER project possible, PowerLight was able to realize the following significant achievements during the development of the PowerTherm™ product.

- Identified lucrative target markets for PowerTherm™ in pool heating applications within Hawaii and California.
- Developed a unique product concept consisting of an inexpensive, flexible, thin film technology bonded to commercially available unglazed solar thermal collectors.
- Achieved advanced manufacturing and fabrication through the development of unique lamination equipment and materials for product commercialization.
- Developed and installed six working systems for testing and performance verification purposes.
- Conducted extensive applicable certifications research including work with ICBO, UL, and European certification standards.
- Developed a marketing plan for the successful commercial deployment of PowerTherm™.

The result of this work is the development of a PV/T product with an installed cost that is 25% less than the cost of two separate systems, and has half the footprint. The success of this PIER project has resulted in the development of a viable commercial product, which will provide customers with a cost-effective, environmentally conscious energy generation alternative. With further manufacturing improvements, advanced testing and validation through demonstration and test units, and focused market development, PowerLight's PowerTherm™ product can become successfully deployed in target markets such as California and Hawaii.

1.0 Introduction

It has long been recognized that photovoltaic modules, while operating, produce a large amount of heat, which lowers efficiency; on a hot day, modules may only produce only 70% of the manufacturer's rated power. An ideal solution would be a combination photovoltaic-thermal collector that captures and uses the excess heat, thereby improving PV performance. However, past research to design such a system has not led to any commercially viable – that is, affordable – product. Under this PIER contract, PowerLight sought to design a thermal collector system that pays for itself in 5 years or less as measured against the cheapest fossil fuel competitor available.

The purpose of this report is to document the research and development effort of PowerLight during the PowerTherm project. This report will outline the work undertaken during the development of PowerTherm from June 1998 through March 2002. This document highlights the achievements accomplished during this period and offers conclusions, recommendations, and suggestions for future work.

1.1. Background and Overview

A combination solar thermal and photovoltaic system appears attractive at first inspection, but closer study reveals formidable technical challenges. The two parts of such a system share only one component - the solar resource. Beyond this, they have nothing in common, incorporating completely different trades, applications, and materials.

An extensive body of literature exists in this field, which has predominantly focused on area efficiency. This parameter, however, is not the most important indicator of collector performance. Rather, the cost/benefit ratio is the most important factor from a market perspective, as indicated by the success of the solar pool heating industry.

Cheap, low-temperature, low-efficiency collectors that have a cost/benefit ratio low enough that the systems pay for themselves in 3-5 years against natural gas dominate pool systems. These systems are widely accepted, and the market continues to grow. Medium temperature systems that use glazed copper collectors for domestic hot water (DHW) offer much higher area efficiency than an unglazed collector, but the total system cost is so much higher that payback is 30+ years against natural gas. There is no commercial market for these systems at this time.

1.2. Project Objectives

1.2.1. Technical Objectives

The overall objective of this project was to develop a hybrid PV/T roofing product that would increase the economic value of a PV roof-tile. By integrating a solar thermal collector with a PV array, owners receive the added benefit of producing heat with little added installation and maintenance costs. The specific technical objectives were to:

- Improve heat transfer between the PV laminate and solar-thermal absorber by 40%;
- Increase the effective irradiance of the sloped collector by 5%;
- Increase the thermal performance of the overall system by 35%;

- Improve the overall system efficiency by 45%.

PowerTherm, as designed, meets the objectives of this project. Over the course of this project – and numerous design iterations – PowerLight designed and tested numerous product concepts, modifying components and manufacturing techniques, to improve overall system efficiency. Each objective is discussed in turn.

1.2.2. Economic Objectives

PowerLight successfully met both economic objectives of the project. Through careful study of potential PV/T market opportunities and analysis of PowerTherm's capabilities, PowerLight identified appropriate target markets for the product as well as product elements to best serve those markets. The economic objectives for this project were to:

- Integrate thermal components into the PV assembly for less than $6 per square foot;
- Achieve a thermal component payback of less than 5 years in potential target markets.

1.3. Report Organization

Section 2.0 describes the project's scope of work as well as the initial market research, initial design development, advanced product development, manufacturing and fabrication development, testing and verification, certification, and market development components of product development. The project's outcomes and achievements are discussed in Section 3.0, and its conclusions, recommendations, and benefits to California are explored in Section 4.0.

2.0 Project Approach

PowerLight takes a "value" approach to engineering, focusing its research effort on the payback period of a particular system design. This was done through extensive computer simulation of site conditions with a custom version of the Transient Energy System Simulation Tool (TRNSYS) and the PVGRID PV simulation tool. Different materials and configurations were tested against a typical hotel DHW load and pool-heating load in two different locations, Hawaii and California. 1000 years of simulation studies (in time steps of 15 minutes) were used to find a system design that would be most cost-effective, meet established building codes, and use off the shelf components.

By focusing on customer needs and real world conditions, PowerLight has designed a thermal system that can compete with fossil fuel alternatives and pays for itself in less than 5 years for pool heating loads. This system does not provide the highest area efficiency or even 50% of the customer's thermal load. However, it does provide customers the opportunity to invest in a system that will provide concrete benefits at an attractive payback rate and will improve the market penetration of photovoltaics and solar thermal at the same time.

In order to quickly develop and test initial product concepts, PowerLight leveraged its prior development experience by integrating PowerLight's PowerGuard© product with off the shelf solar thermal collectors. A PowerGuard tile consists of a flat plate PV laminate mounted onto a flat, rigid, extruded polystyrene (XPS) board. PowerGuard tiles fit together with tongue and groove edges, in an interlocking fashion. The array generates DC current, which passes through a DC/AC inverter and transformer en route to the building's electric service.

The PowerGuard tile concept provides an easy way to install PV, and provides roof insulation as an added benefit. However, ergonomic concerns and roof realities restrict the maximum size of a PowerGuard tile to approximately 20 square feet. While this is ideal for PV, thermal collectors are better installed in 40 square foot increments because of the cost of plumbing interconnections. Also, when heat is extracted from the collector surface, insulation is no longer useful. Furthermore, DHW applications proved to be very complicated and expensive to install because of the large heat exchangers required. These findings ultimately led the design team to the current design of PowerTherm, which focuses on a residential pool heating PV/T assembly that mounts directly to the roof surface, instead of the original flat roof commercial DHW application.

2.1. Scope of Work

The scope of work under this contract included the following:

- Initial Product Development - Develop preliminary tile construction design composed of PowerGuard and solar thermal absorber;
- Market Planning - Identify selected markets for cost effective installation of PowerTherm; develop market entry strategy for the solar thermal market;
- Advanced Product Development - Improve on PowerTherm's performance while reducing overall system cost;
- Testing and Verification - Perform accelerated life testing to ensure product reliability in the field; install and monitor demonstration system to verify performance;

- Manufacturing Development - Develop a manufacturing plan for large volume production;
- Certifications – Conduct testing for certifications, including Underwriters Laboratories (UL), Florida Solar Energy Center (FSEC), International Conference of Building Officials (IBCO), and relevant international certifications;
- Business Development - Identify partners for successful production and marketing of PowerTherm; create education and training programs for contractors in sales, installation, and maintenance; develop business and finance plan; develop commercial partnerships.

2.2. Initial Market Research

The development of the PowerTherm product benefited from early market analysis suggesting that an unglazed collector was the best PV/T collector for the target market. An unglazed collector configuration provides a very good match between the area needed for pool heating and the area needed for electricity generation for an American or European household. Many PV/T systems focus on medium temperature DHW heating; a typical house, however, needs only a maximum 40 sf of DHW collector, which is not enough area to meet the customer's electrical load. The customer must then cover additional roof area with PV material to satisfy her electrical needs and then integrate two different PV systems with different operating characteristics into the household electric system. With similar area needed for both the PV and thermal elements, PowerTherm avoids this problem.

There is much speculation about PV/T applications in the developing world. However, PowerLight's market research has shown that while there is a large potential market for PV in the developing world, hot water remains a low-priority luxury for most households. On the other hand, hot water is needed for hotels and other commercial enterprises throughout the world, and an unglazed collector serves these loads more cost effectively than glazed medium temperature collectors because of lower first cost and better performance at low inlet temperatures. This is a potential market, albeit in the future.

2.2.1. Market Entry Strategy

To determine the best way to successfully sell PowerTherm to end users, PowerLight interviewed both solar installers and prospective customers and developed a set of models to determine the financial costs and benefits associated with owning PowerTherm over its useful life.

2.2.1.1. Residential System Interviews

PowerLight staff interviewed San Francisco-Bay Area solar contractors to solicit feedback on the PowerTherm concept. The contractors were enthusiastic about the product but were concerned about long-term reliability, a normal concern for any new product. They also wanted the product to install in the same way as current solar pool equipment, to minimize training needs. Some contractors felt that PV customers and pool customers are fundamentally different market sectors, and that there is little overlap in the kind of customer who owns a pool and the kind of customer who is willing to invest heavily in green electricity. However, other contractors were just as confident that the reduced per unit cost of a combined PV/T installation would provide a large incentive for installing PV.

A number of potential pool customers were also interviewed to assess their desire to buy a combination PV/T product. The people interviewed were very excited about meeting the electrical and thermal needs of their swimming pool with solar energy. They also preferred to have one type of solar panels on their roof, instead of two different systems, for both aesthetic and ease-of-use reasons.

The most important factor by far to both customers and installers was the cost-effectiveness of PowerTherm versus other products or combinations of products on the market. Since energy costs and tax benefits vary widely from state to state and country to country, it was important to simulate actual and avoided costs and savings, using financial spreadsheet models, depending on a customer's geography.

In California, a rebate is available to residents for $4.50/watt or 50% of system costs whichever is less. Therefore, a residential customer would receive a rebate of $3/watt for the PV portion of the system, making the net cost $3/watt. In a 1996 IEEE paper, "Niche Markets for Grid-Connected Photovoltaics," Howard Wenger, et al, calculated that the break-even price for PV was $4.80/watt in California if the customer financed the system with a mortgage. If other states had a similar rebate structure, a PowerTherm PV/T pool heating system would be cost effective in 25 states. Hawaii is currently the only other state that provides a substantial solar incentive, and the break-even price as calculated in the study was $7.50/watt. Therefore, Hawaii and California are currently cost effective markets for PowerTherm and, as such, are the main focus of marketing development.

2.2.1.2. Large System Interviews

PowerLight also explored the market for larger commercial systems. While the focus of this project was primarily residential systems, these initial interviews indicated a greater market for this product. In a series of on-going, informal interviews with potential commercial customers, PowerLight found that while cost effectiveness is a primary issue, a range of non-economic factors emerged as important.

One major factor is a local authority or county's desire to demonstrate environmental stewardship. In Northern California, there are many non-specific government resolutions and directives relating to setting up environmentally friendly policies and procedures. These directives enable motivated government employees to pursue environmental solutions. Environmental policy statements are not limited to governments. There has been recent interest in solar products by a number of corporate customers that have decided that solar power offers a combination of environmental benefits, business goals, and positive public relations. The perseverance of individual "champions" with environmental convictions is often why environmentally oriented projects are done at large organizations.

A key value proposition discovered during these interviews was the way in which avoided utility and operational costs are considered an acceptable way to pay for an environmental project. For example, a significant portion of the cost of PowerTherm could be paid by the avoided costs associated with the replacement of aging and inefficient water heating and cooling equipment for a particular facility. By bundling project costs and benefits, the decisionmakers at the organization can take a holistic view of one large project rather than looking at the specific payback of each project part.

2.3. Initial Design Development

Initial design development focused on creating a system with off-the shelf components, leaving custom development for the advanced design phase. At the start of the project, PowerLight intended to create PowerTherm by integrating solar thermal collectors with the PowerGuard system. This would involve adhering the collectors to the underside of polycrystalline PV modules. Below (Figure 2) are initial product concept diagrams.

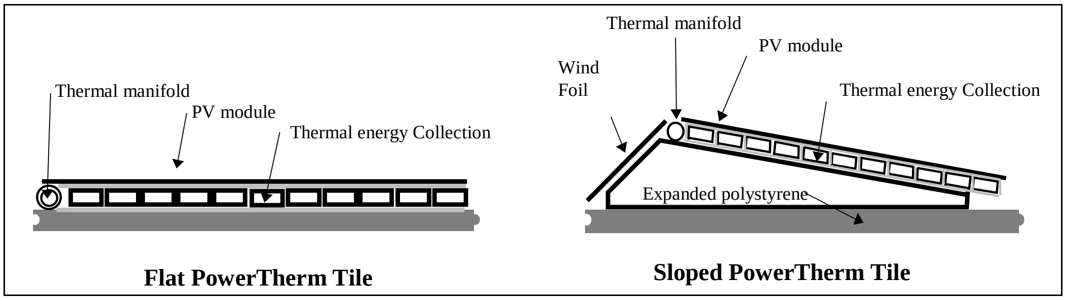

Figure 2: Initial PowerTherm concepts incorporating PowerGuard

Initial areas of focus included choice of collector material, open-loop system versus closed loop, gallons of storage per square foot of collector, flow rate of collector loop, and square foot of collector per unit of thermal load.

Collector design was investigated first as there were many possible materials in terms of PV laminates and absorbers. The collector designs evaluated were different combinations of copper and plastic absorbers and laminates composed of two layers of glass or a top layer of glass with a Tedlar backing. Extensive simulations were run; changing one parameter at a time to observe the impact on performance. Annual collected energy value was divided by cost to compare different materials.

PowerLight found that the system that performed best was a laminate adhered to a polypropylene pool collector, with a flow rate of 2 gpm in a closed loop configuration, with little or no storage. The collector with the best area to load ratio was found to be the minimum size evaluated during this simulation. This system served approximately 15% of the annual DHW thermal load at the simulated site. The payback for a system this size was calculated to be less than 5 years.

Further development focused on collector design and balance of system (BOS) improvement. The goal for the collector design was to manipulate laminate and absorber parameters to improve collector efficiency and reduce costs. The goal for BOS components was to reduce overall costs.

2.3.1. Collector Design

The goal of the initial collector design was to improve heat transfer between the laminate and absorber, streamline the attachment of the absorber and laminate into a collector, and reduce top losses from the laminate to improve collector efficiency in windy or low ambient temperature conditions. Simulation studies showed that small changes in collector construction yield net gains in heat production of up to 45%.

Initial work identified a number of ways to improve thermal performance based on collector design. One method was to increase the thickness of the top encapsulant layer. The encapsulant in the laminate has excellent optical properties and insulates 150 times better than air for the same thickness. Furthermore, the encapsulant blocks convective heat transfer completely, much like a stratified solar pond. Light passes through, strikes the PV cell, and generates electricity and heat, which is trapped by the encapsulant.

Initial study showed that a layer of encapsulant as thick as 0.25" could be applied with an incremental cost of $2/sf. This thickness, when tested in simulation, showed stagnation temperatures of 250°F, too high for the present components. Decreasing either that thickness or the insulation on the back of the collector can reduce the stagnation temperature

Another way to improve thermal properties is by bringing the PV cells and absorber closer together. If encapsulant thickness between the laminate and absorber is reduced, heat transfer is increased, and electrical performance will be moderately improved by the reduction in temperature gradient between the laminate and absorber. This finding was the basis for further work on this project.

The final improvement considered at this stage of development was the use of thin film amorphous silicon PV technology. This technology has great promise because it reduces the distance between the PV materials and the absorber to microns, improving heat transfer, but it is not without technical challenges. PowerLight worked closely with a thin film manufacturer to incorporate this technology into the project.

2.3.2. Optimized Balance of System Components

Balance of system components and installation labor were important to study because they comprise 65% of the total installed cost of the PowerTherm system. System components are summarized in Figure 3 below and detailed in the following sections.

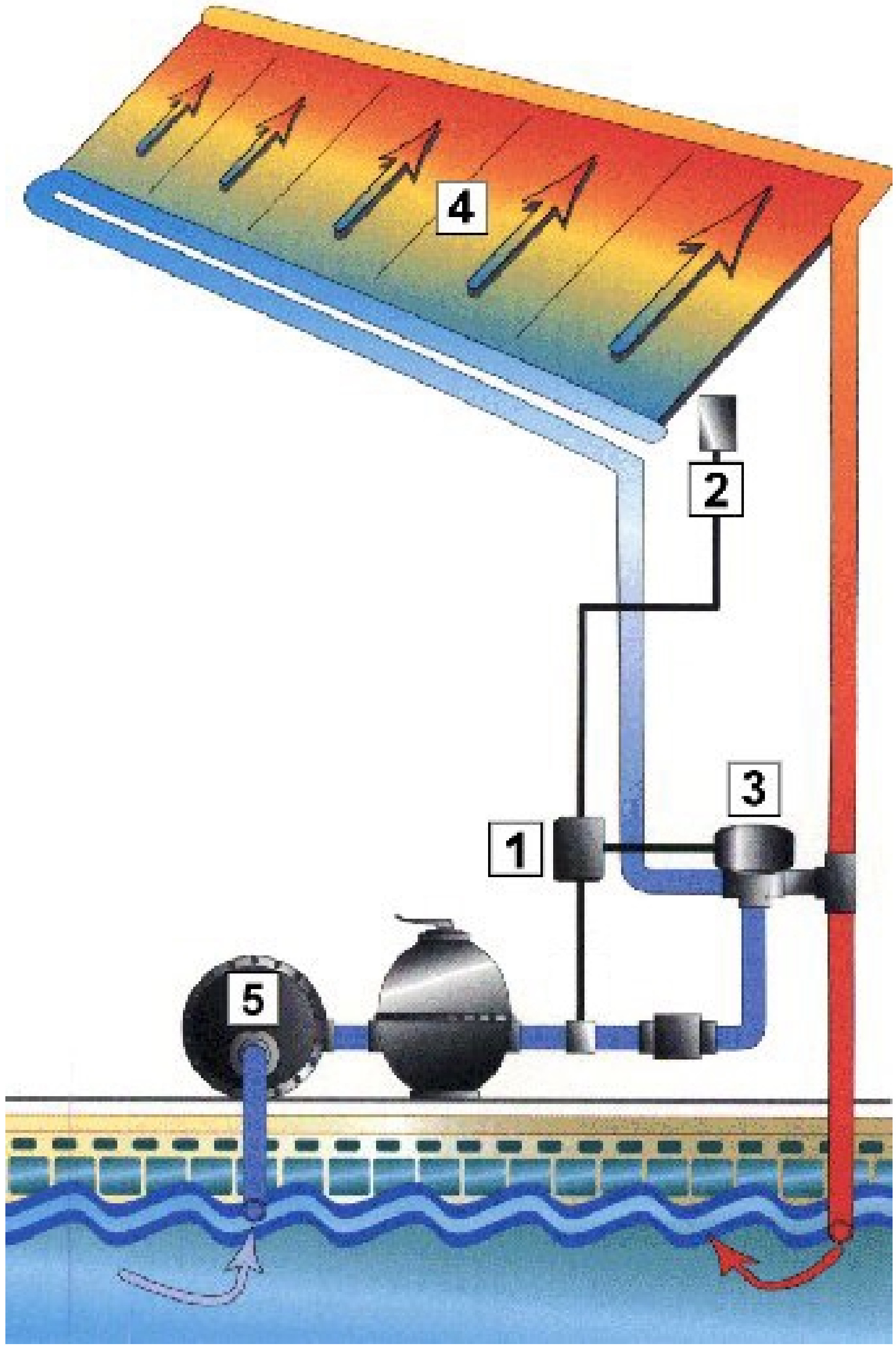

Figure 3: Balance of system diagram for solar thermal system: 1. Controller, 2. Sensor, 3. 3-way valve, 4. Collector, 5. Pump

2.3.3. Thermal Controls

PowerLight identified a high quality thermal controls unit to be used for the pool heating components on residential and commercial installations. The control senses roof and pool temperature and cycles an automatic three-position valve if the array is warm enough to provide useful heat. This unit is the industry standard and is entirely suitable for any PowerTherm application from 200 sf to 10,000 sf. Some applications may require a booster pump if the static head is too high for the existing filtration pump.

2.3.4. Inverters

PowerLight also identified an inverter from a manufacturing partner that would be the proper size and voltage for a residential pool heating application. This manufacturer has a variety of inverter models, which could be used for larger-sized systems. One option is to directly power the pool filter pump using a DC motor and thus use no inverter at all. It was concluded, however, that using an inverter and connecting to the grid is most cost effective primarily because a typical direct-drive PV pumping system needs 15-20% more PV capacity than the nominal power rating of the pump to enable early morning and late afternoon operation. A direct drive application is attractive for new installations when the cost of pool electrical equipment installation is higher than the cost of the additional PV required for a direct drive application. It may also make sense if the pool is far from electrical supply, or if the house has a low power electrical service and would require a system upgrade to accommodate the filter pump. The difference between time-of-use (TOU) rates and standard rates is also important. Utilities often do not allow grid interconnection with a time-of-use schedule. However, a customer using the filter pump with direct drive PV may be able to save money by using TOU.

2.4. Advanced Product Development

2.4.1. Design Development

It was at this stage that PowerLight pursued an alternative design concept, identifying a flexible thin film PV product under which solar thermal collectors could be integrated. This design became the basis for further product development, the advanced stage of which focused on materials research and the method of mechanical attachment between the solar collector and the PV module.

To determine the best method for mechanical attachment, PowerLight tested more than 40 adhesives and 3 different encapsulant formulations for lamination. Adhesion and lamination pathways have been extensively characterized, with an emphasis on manufacturing cost and throughput. At the end of this phase of development, it was concluded that lamination would be the preferred method of attachment as it offers the lowest cost, highest throughput, and strongest attachment. Adhesion initially was attractive due to low tooling costs. However, quality control is difficult and application is labor intensive. PowerLight selected a manufacturer to develop a custom bonding layer material to laminate the absorber material directly to the PV backing with no surface preparation needed. Below, in Figure 4, is a picture of the PowerRoll prototype, the embodiment of the PowerTherm product that integrates with a flexible thin film laminate.

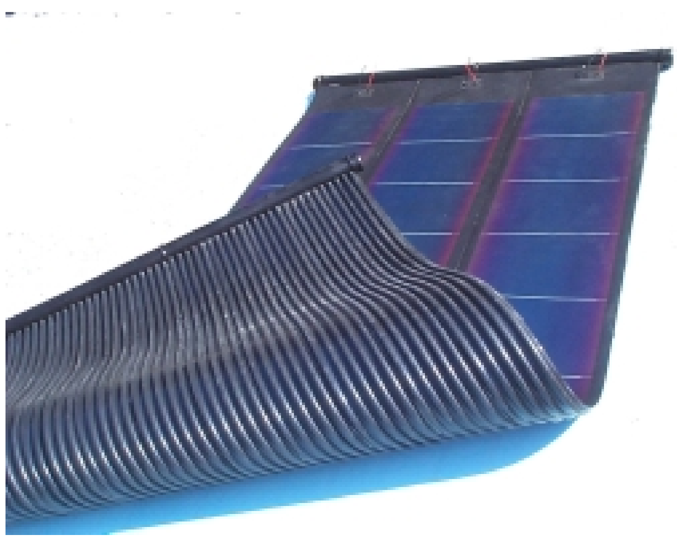

Figure 4: PowerRoll - embodiment of thin film PV integrated with EPDM solar thermal collector

2.4.2. Materials Research

An ethylene propylene diene-monomer (EPDM) formulation made by a solar collector manufacturer was chosen as the thermal collector material. PowerLight developed a commercial alliance with the manufacturer of this component. Ethylene propylene co-polymer made by another manufacturer was also tested, but the low surface energy of the material made it impossible to bond via adhesion, and the high modulus of elasticity caused an unacceptable amount of strain in laminated samples. A third absorber candidate, poly-vinyl chloride (PVC), had high surface energy, which allowed for strong adhesion. However, the PVC material melted in the laminator, and the water cavities inside the absorber melted shut. Therefore, the only way to bond PV to the PVC is adhesion, which is not the lowest cost alternative until a cheaper adhesive with less need for surface preparation is discovered.

Another reason that EPDM made by the selected manufacturer was chosen is that this material has never exhibited the "black pool syndrome" that caused other manufacturers of EPDM to go out of business. The EPDM formulation found in these unsuccessful products degraded over time due to exposure to high chlorine levels commonly found in pools. The carbon black in the absorber material precipitated onto the bottom of the pool as the material broke down, causing many warranty claims from unhappy customers. PowerLight's EPDM manufacturer has never had a customer complaint due to this problem, with thousands of systems still in service. Additionally this manufacturer produces standard products that match standard sizes identified for the PowerTherm product.

2.4.3. Mechanical Attachment

The fundamental manufacturing task for this product is to bond the EPDM thermal collector to the flexible PV laminate and other PV substrates. Finding a suitable adhesion method involved a thorough investigation of various adhesive types, application methods, and surface preparation techniques.

Through extensive testing, PowerLight and its adhesion consultant analyzed possible adhesives that could bond EPDM to various PV substrates, which would be used in the final product. A second experiment focused exclusively on which adhesives would stick to the flexible PV substrate. A sampling of different adhesives was selected based on tensile strength, flexibility, and recommendations from manufacturers and distributors. PowerLight determined that the final adhesive and bond line should have the following characteristics:

- High tensile strength
- Flexibility, elongation
- Service temperature
- Peel resistance
- Ability to withstand long-term outdoor exposure

The critical requirement was a dramatically higher tensile strength requirement than previously estimated; this eliminated all the adhesives previously investigated. The largest challenge faced during this work was that the standard back substrate of the PV had a relatively low surface energy, which explained the difficulty in achieving a strong, durable bond to the PV backing.

Testing and research was done to increase the tensile strength of the bond between the PV and thermal collector, including an examination of heat activated bonding layers and hot melt adhesives. Plasma discharge and chemical etching were investigated to modify the surface of each material in preparation for bonding. Various cleaners were also considered; however, some solvent cleaners found presented a major workplace safety issue due to very high levels of VOCs (Volatile Organic Compound). Additionally work was conducted with our PV laminate manufacturer to explore alternative back skin materials.

In total, 6 types of adhesives were investigated, which produced 13 different adhesive possibilities to be tested, using coupon-sized samples of various bonding materials and processing methods.

2.4.4. PowerRoll Prototype

Following these tests, PowerRoll, the first prototype using the flexible thin film PV laminate was created. The prototype was created using the adhesive that yielded the most promising results from the tests discussed above. This adhesive was chosen based on its high elongation (very flexible), zero toxicity, low cost, proven ability as a roofing product, and its good preliminary results in bonding EPDM to the PV laminate back skin.

We used the vacuum lamination method to successfully bond a 9’ x 4’ prototype. The figure below shows the apparatus and application method. The PV modules were laid into the table, back skin side up. The back skin was cleaned thoroughly with acetone. The EPDM absorber was cleaned with acetone, sanded, rinsed once more with acetone and set aside. Figure 5 shows the application of the adhesive. After the adhesive was applied and spread evenly, the absorber was lowered into position, as seen in Figure 6. The plastic sheet was then placed on top and the assembly was placed under vacuum for 16 hours (Figure 7). The finished product, PowerRoll, is shown in Figure 8.

Figure 5: Applying adhesive to prototype with air powered adhesive guns

Figure 6: Placing cleaned EPDM absorber onto adhesive layer

Figure 7: Vacuum bag in place and vacuum pump is on.

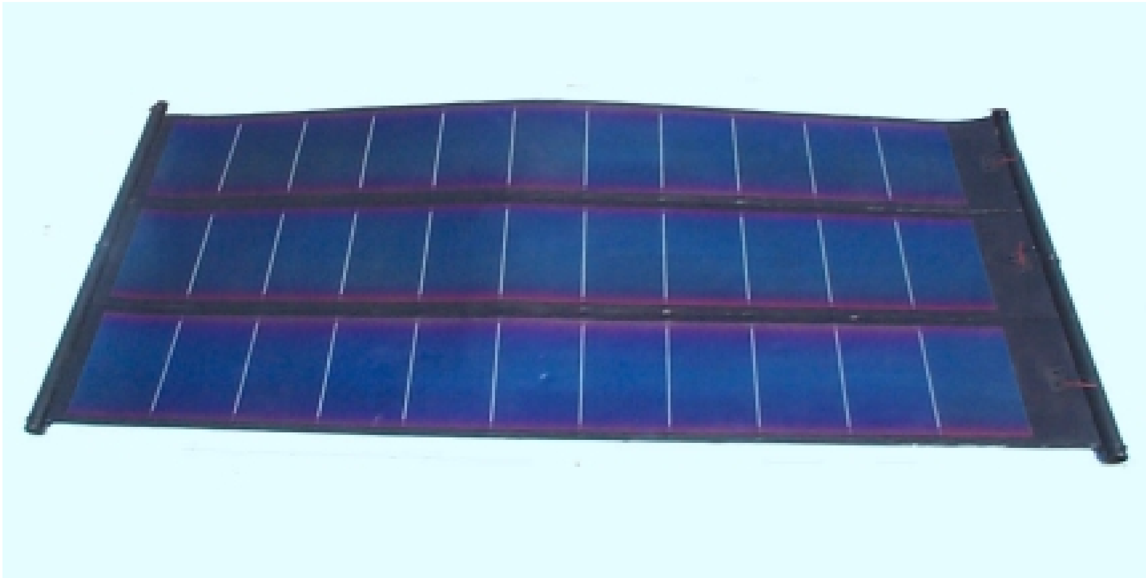

Figure 8: Completed PowerRoll prototype assembly

Using a room temperature curing adhesive presents major difficulties in achieving fast throughput and low production cost for large surface areas. The most common solution in commercial production is to use heat as an accelerator. Initially we dismissed using heat activated adhesives for fear of damaging the substrates with hot melt adhesives and the high equipment cost with a lamination cycle. However, in light of the drawbacks of room temperature adhesives, higher equipment costs could be offset by much faster throughput. Production type PV laminators can have cycle times as short as 10 minutes. This design improvement became the focus for further product development efforts.

2.5. Manufacturing and Fabrication Development

The primary focus of this stage of the project was to identify the manufacturing process to mechanically attach the PV laminate to the thermal collector.

2.5.1. Materials Research

2.5.1.1. Bonding Layer Development

PowerLight worked closely with a custom manufacturer of bond material to develop a specialized formula for the bonding layer. Test laminations of 2″x3″ samples, including creep tests and preliminary freeze-thaw tests, had favorable results. Accelerated life testing on larger-scale samples was also performed. This test showed that the bonding layer lacked adequate strength to withstand the differential thermal expansion stresses imposed by the thermal cycling regime. Research by the bonding layer manufacturer has identified other bonding layer material options, which will need to be tested further.

Characterization of material response to lamination conditions was undertaken in order to determine which materials were the limiting factors in determining lamination parameters. Exposure to low ambient pressures at moderate temperatures does not harm any of the materials. Therefore, the main area of concern in the lamination process is to identify the temperature exposure limit both in terms of temperature and duration of exposure at a given temperature. The critical material was determined to be the PV module itself, followed by the EPDM material. The bonding layer was found to be more robust than the other materials under lamination and therefore is not a cause for concern.

2.5.1.2. PV Laminate Module

The PV modules are prone to de-lamination near the bus bars and other areas of physical discontinuity when subjected to temperatures and/or temperature transition rates necessary for the lamination process. This problem was first encountered in the laminations made in an oven. The de-lamination results in a loss of bond integrity between the top skin of the module and the solar cell itself, which creates a visible defect. These defects are small and do not appear to affect the ability of the cell to produce power, but if they were to enlarge over time they could cause the module to come apart completely. PowerLight believes that the best way to solve this problem is to laminate the EPDM to the PV laminate components when the PV module is assembled.

2.5.1.3. EPDM

While the EPDM did not appear to suffer ill effects from the lamination process, there was concern about it becoming brittle because of the temperature and time under vacuum. Low ambient pressure coupled with exposure to temperatures as high as 150°C could cause the more volatile components of the rubber to evaporate, leaving the rubber in a brittle condition. This could lead to premature failure in the field, so testing was initiated to try to identify the potential magnitude of the problem.

A series of tests evacuated EPDM samples to less than 1″ Hg absolute and subjected them to temperatures of 160°C for 15 minutes in a small laminator. The samples were then pull tested to find elongation at break and ultimate tensile strength. Within the margins of error of the test, there was no difference between the control samples and the experimental samples. The picture below Figure 9 shows the test setup.

Figure 9: EPDM test setup

Lamination Studies

Extensive adhesion studies were done to identify possible methods for room temperature adhesion. None satisfied targets for cost and manufacturing throughput. Lamination was, instead, the process chosen. Heat activated adhesives are applied in solid form and activated by heating the materials to 150°C and placing them under a vacuum. Lamination is commonly used in the PV industry to package modules.

Lamination has 4 phases. “Pump down” brings the sample from atmospheric pressure to the desired lamination pressure. “Ramp” is the heating phase, expressed in degrees per minute. “Soak” is a temperature plateau at a specified temperature to allow the materials to cure and bond. The “Cooling” phase is essentially a negative ramp.

The goal of any manufacturing process is to produce good quality product quickly. Quality and throughput are usually conflicting goals, so the task is to strike a balance between the two. For fastest throughput, all four phases of the lamination cycle need to be done as quickly as possible. State of the art PV laminators can produce finished parts in as quickly as 10 minutes. However, these units cost as much as $250,000, and were not within reach of the project budget.

PowerLight surveyed available equipment and lamination strategies in the PV and other industries. The biggest challenge was to find a laminator that could attain a high vacuum, an original design constraint based on specifications from the adhesive manufacturer and PV industry practice. Lamination work was carried out on 3 different pieces of equipment. The first trials used a flat plate of aluminum, in Figure 16, machined to support the EPDM tubing, which was heated in an oven. Knowledge gained from this work was applied to the design of a Small Scale Laminator, seen in Figure 17, which was used to manufacture 1/10 scale PowerTherm samples. A third round of testing was carried out on a wood product laminator, pictured in Figure 18 large enough to accommodate a full size prototype. Knowledge gained from this work will be used in future development efforts to design a full scale PowerTherm laminator capable of producing 10 finished collectors per shift.

2.5.1.4. Flat Plate Laminator

Figure 10: Flat plate laminator

The picture, Figure 10, above shows the flat plate laminator designed to mimic the lamination process of the PV module used in this product. Laminations were successful, yet the heat transfer rate was very slow, and the thick aluminum plate required approximately 1.5 kWh to heat, which took more than 1.5 hours in the 90 kW oven. Cooling the system took 1-3 hours using fans and water spray.

2.5.1.5. Small-Scale Laminator

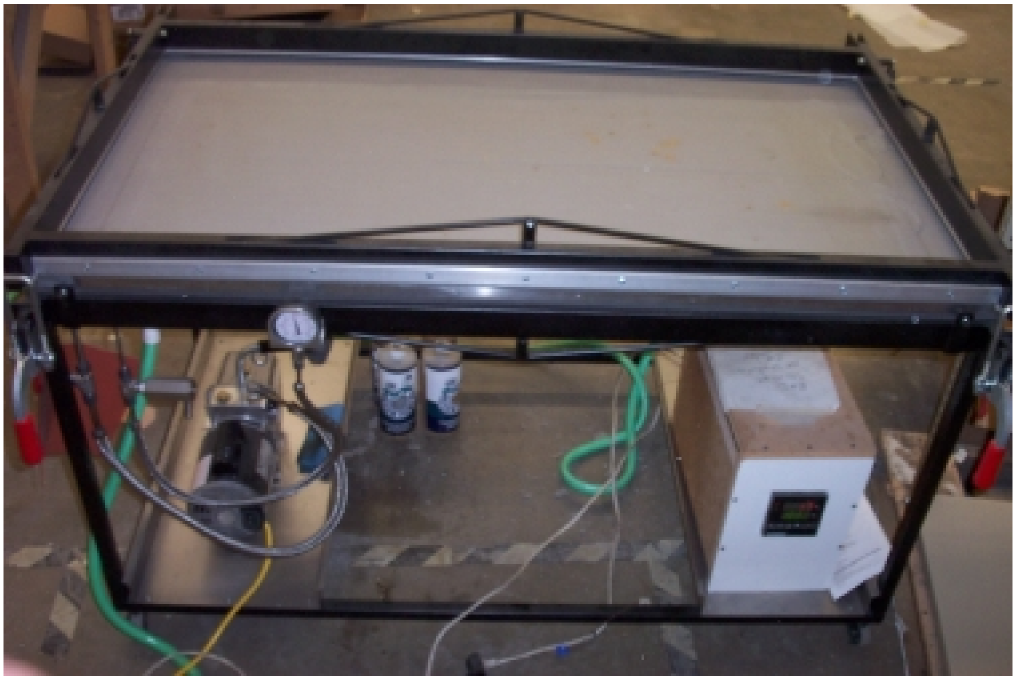

Figure 11: Small lamination table

PowerLight, assisted by an equipment fabrication specialist, designed and built a small-scale lamination table Figure 11, to accommodate a 3-cell PV module laminated to 4 sample strips of EPDM material. The laminator was used to better understand the lamination process and to create samples for materials and process studies.

2.5.1.6. Full-Scale Laminator

Figure 12: Full-scale lamination table

2.5.1.7. Design and Fabrication of Custom Laminator

PowerLight originally planned to fabricate a full-scale laminator (Figure 12) based on the small-scale lamination experiments. However, in the course of building the small-scale laminator, many issues arose concerning difficulties in the design of this type of equipment, and development of a large-scale laminator was delayed in favor of further testing and using off-the-shelf equipment.

2.5.1.8. Laminator Investigation

Figure 13: Lamination table in Oregon

A substantial amount of effort was put into finding a manufacturer of equipment outside the PV industry that could build a machine to the original design requirements. The most challenging requirement was the very low pressure in the original specification; the second was temperature control. The cure properties of the bonding layer implied that a tight temperature control specification is needed for minimum cycle time.

PowerLight located a large press laminator (Figure 13) in Oregon and rented it to fabricate 4'X10' prototypes. The machine produced good results when the machine temperature was controlled manually and the temperature at different points was carefully monitored (in real time, using an array of thermocouples read by a data logger). Temperatures were monitored at various positions on the prototype and set points manually adjusted.

PowerLight developed a strong relationship with this lamination manufacturer. Working with this company gave us valuable manufacturing information and experience. This relationship also offers PowerLight options once PowerTherm moves closer to product launch. Discussions have explored the possibility of this company taking on PowerTherm manufacturing and/or selling their equipment to PowerLight.

2.5.1.9. Critical and Optimal Lamination Parameters

Achieving high-quality lamination is at the heart of PowerTherm research and development. The challenges in the lamination process are primarily bubble formation in the bonding layer, proper curing of the bonding layer, and de-lamination of the solar module itself caused by melting or softening of the EVA which holds it together. A secondary consideration from a quality standpoint, but a primary one from the standpoint of economic viability, is lamination cycle time. The following table (Table 1) summarizes the lamination parameters and the goals they affect. The "+" indicates a positive impact, while the "-" indicates a negative impact. It is necessary to balance these parameters in order to meet both quality and cost goals for the lamination process.

Table 1. Lamination Parameter Matrix

	Lamination Goals				
Lamination Parameter	**Eliminate Bubbles**	**Eliminate De-Lam**	**Full Cure of Bonding Layer**	**Minimize Cycle Time**	**Equipment Cost**
High Soak Temp		-		+	
Tight Temperature Control		+	+	+	-
Slow Ramp Rate	+	+		-	
High Cool Rate				+	-
High Vacuum Level	+			+	-
Bonding Layer Thickness	+				

2.5.2. Material Preparation and Handling

2.5.2.1. EPDM Scrubber

One of the manufacturing tools developed during this project was the "rubber scrubber" (Figure 14) that was built to prepare the EPDM material by roughing its surface and mechanically removing mold release chemicals. It was built and largely designed by PowerLight's equipment fabrication specialist. The cut rubber tray is built to accommodate ten 10-foot long strips of EPDM and is angled for easy removal of the cut strips.

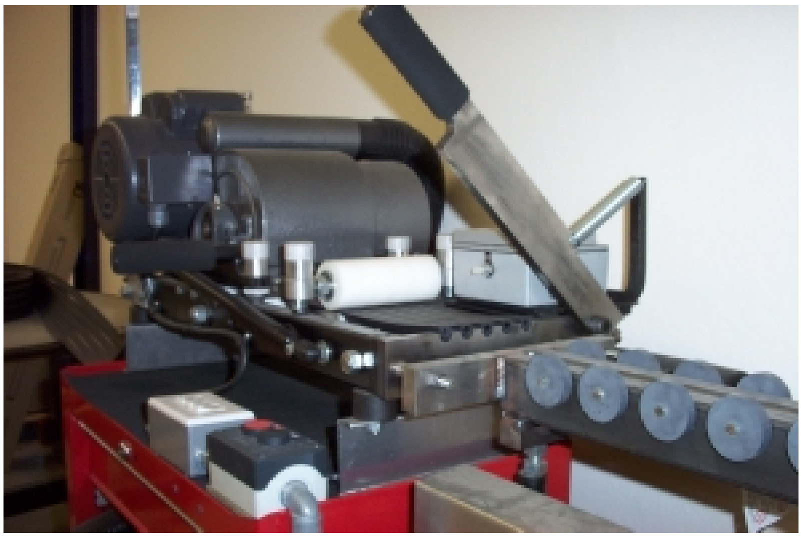

Figure 14: EPDM scrubber equipment

2.5.3. Manufacturing Process Development

Before lamination, materials must be dispensed, cut, cleaned, and assembled. After lamination, the part must be removed carefully and trimmed, plumbing headers attached, and electrical junction boxes installed. These steps are critical to product quality and must all be done efficiently to minimize cycle time and cost.

Figure 15: EPDM being laid into the table

2.5.3.1. Materials Preparation

The raw materials for the product are the EPDM, bonding layer, and PV modules.

The EPDM must be scrubbed and cut, then aligned and laid into the aluminum support extrusion (Figure 15 and Figure 16). The bonding layer is taken off the rolls, cut to length with scissors, and aligned. Two pieces of bonding layer will cover the width of the collector. Finally, the PV modules are laid into place. They must be straight and butted up against each other. Latex rubber gloves are worn to avoid contaminating materials with skin oils, and every effort is made to keep other sources of contamination from the materials.

Figure 16: PV placed on top of bonding layer in table

The pre-processing requires at least two people, and works most efficiently with three, to carry and place the bulky materials and to reach both sides of the lamination table (too wide for one person to stretch across). Working inside the machine requires working underneath the raised lid and silicone membrane, which restricts access at one end of the machine.

2.5.3.2. Post-lamination Processing

Post-lamination processing includes the removal of the laminate from the extrusion, trimming, and installing headers. To remove a laminate, one end of the collector is worked free from the extrusion, and a wooden dowel is pulled between the extrusion and the collector to break it free – a two-person job. Lifting the collector out of the laminator is a three-person job (Figure 17). The aluminum extrusion then must be re-aligned.

It is then necessary to trim the EDPM square since alignment of the EPDM in the machine to the specifications required for proper header attachment is difficult. The next step is to attach the headers. Attachment of the headers could be done more cost-effectively in the factory if special equipment is developed to do it. (Currently, header attachment is a physically difficult and time-consuming procedure.)

Figure 17: Finished product being removed from table

2.6. Testing and Verification

Throughout the project, PowerLight developed 6 working prototype systems, installed at customer sites and monitored, to validate the overall performance of various design concepts.

2.6.1. Prototype Testing – PowerRoll and PowerGuard Format

Figure 18: PowerGuard based system prototype

Figure 19: PowerRoll prototype installation

In April 2001, prototype arrays were installed in Sonoma, CA, pictured in Figure 18 and Figure 19. Three separate arrays were installed: 9 m^2 6.75 kW of PowerRoll based on the flexible laminate; 7.7 m^2 5.8 kW of PowerTherm based on PowerGuard crystalline tile; and a 10.9 m2 8.2 kW array of EPDM to assess the performance of the absorber material without PV and act as a control sample. The electrically active arrays were connected to the grid.

Both customers are very happy with the performance and appearance of the collectors. With its low profile and dark colors, PowerRoll has the best appearance. The installers preferred it because it is lightweight and unbreakable.

2.6.1.1. Thermal Performance

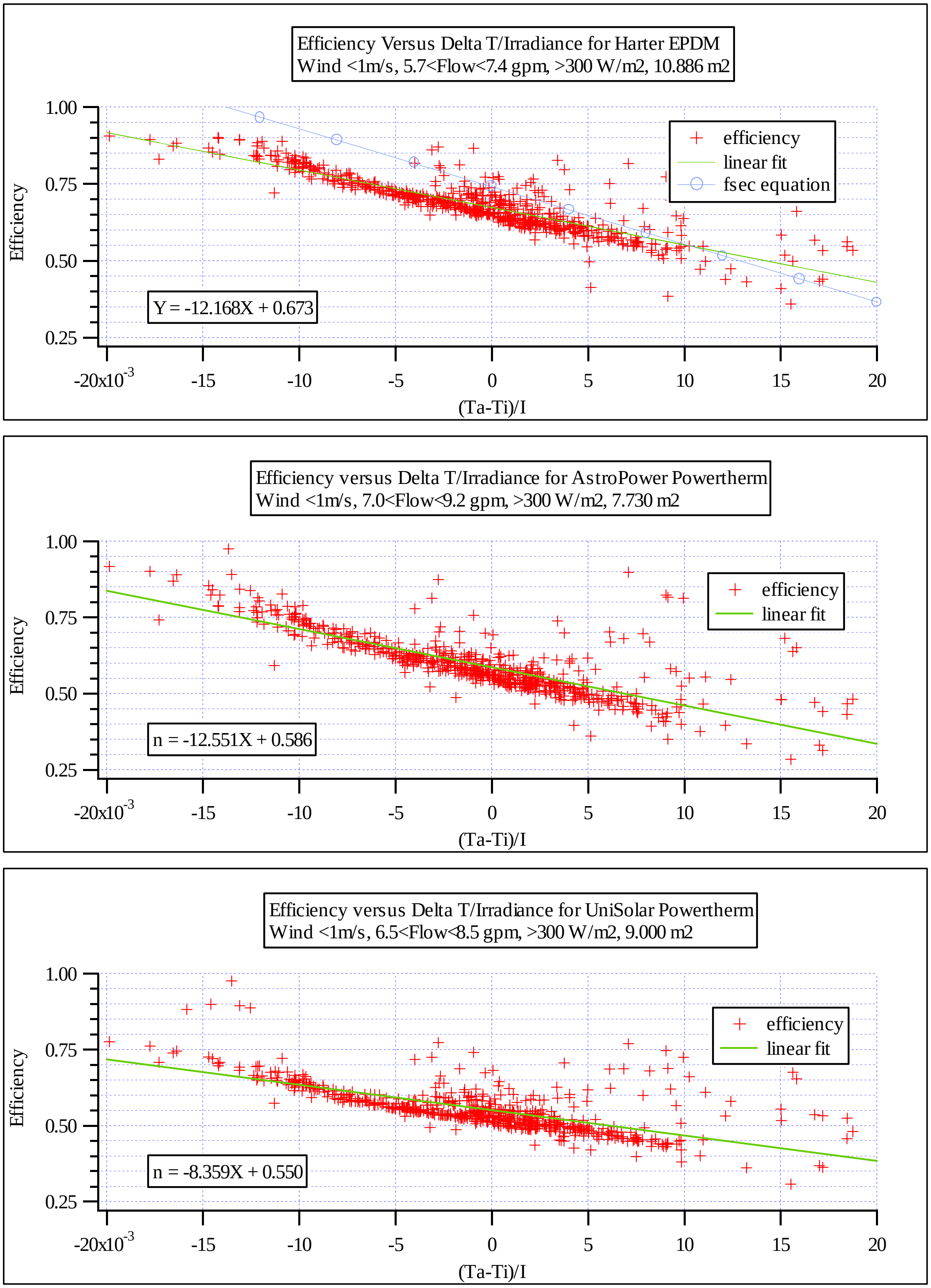

Figure 20: Sonoma, CA. Thermal performance summary

The thermal performance of the 3 Sonoma arrays is shown above in Figure 20. Thermal performance was characterized by plotting thermal efficiency against the difference between entering water temperature and air temperature, divided by irradiance [$(T_i$-$T_a)$/Irr]. A plot of these data points yields a linear curve fit that characterizes the performance of solar thermal collectors under standardized conditions. The intercept value, FRλα, gives the efficiency when air and water temperatures are equal. The slope of the line, FRUL, is related to the thermal losses of the collector. A larger absolute value FRUL (steeper slope) indicates higher thermal losses.

The basic EPDM material is shown in the top plot, with the linear curve fit from empirical data and the representative equation based on Florida Solar Energy Center (FSEC) data. Note that the PowerTherm data were collected from a horizontal array, so incidence angle differences probably account for the different FRλα (intercept) values. Also, the collectors were installed on an insulated roof in Sonoma, versus an open rack mount, so convective losses from the Sonoma system would be less than observed at FSEC, resulting in a lower FRUL (slope) value for all the collectors.

The second graph shows the APTherm, PowerGuard based system, while the third graph show the PowerRoll system performance. Note the similarity in FRλα between the APTherm and the PowerRoll: 0.58 versus 0.55. The APTherm may be higher because of the conductivity of the glass, improving heat transfer across the collector to the water tubes; also, the adhesive layer on the PowerRoll collector is much thicker than the APTherm version. Future versions based on the thin film laminate had a much thinner adhesive layer, which improved heat transfer.

FRUL is much less for the PowerRoll than for the PowerGuard based prototype. This is likely due to the construction of the two different collectors. The APTherm prototype is built like a standard PowerGuard tile with an air gap between the PV/Thermal collector and the tile surface, and the PowerRoll is built with two contiguous layers installed flush on the roof. This latter construction is better insulated due to its contact with the roof and shows less convective losses (smaller FRUL). Clearly, the PV manufacturer material acts as an insulation layer, because FRUL for the PowerRoll prototype is lower than for the EPDM. (Smaller FRUL means that at a ΔT of 25^oC and 300 watts/m^2 irradiance, the two collectors would produce the same amount of heat per square foot, in addition to the electrical output from the PV/T collector.)

Figure 21 shows two typical days for the PowerRoll configuration. The system stagnated with no flow on July 30^{th} and ran normally on July 31^{st}. The stagnation temperature is very similar to temperatures observed for a standard PV installation, because PowerRoll is installed flush to the roof deck like the normal thin film PV roofing product.

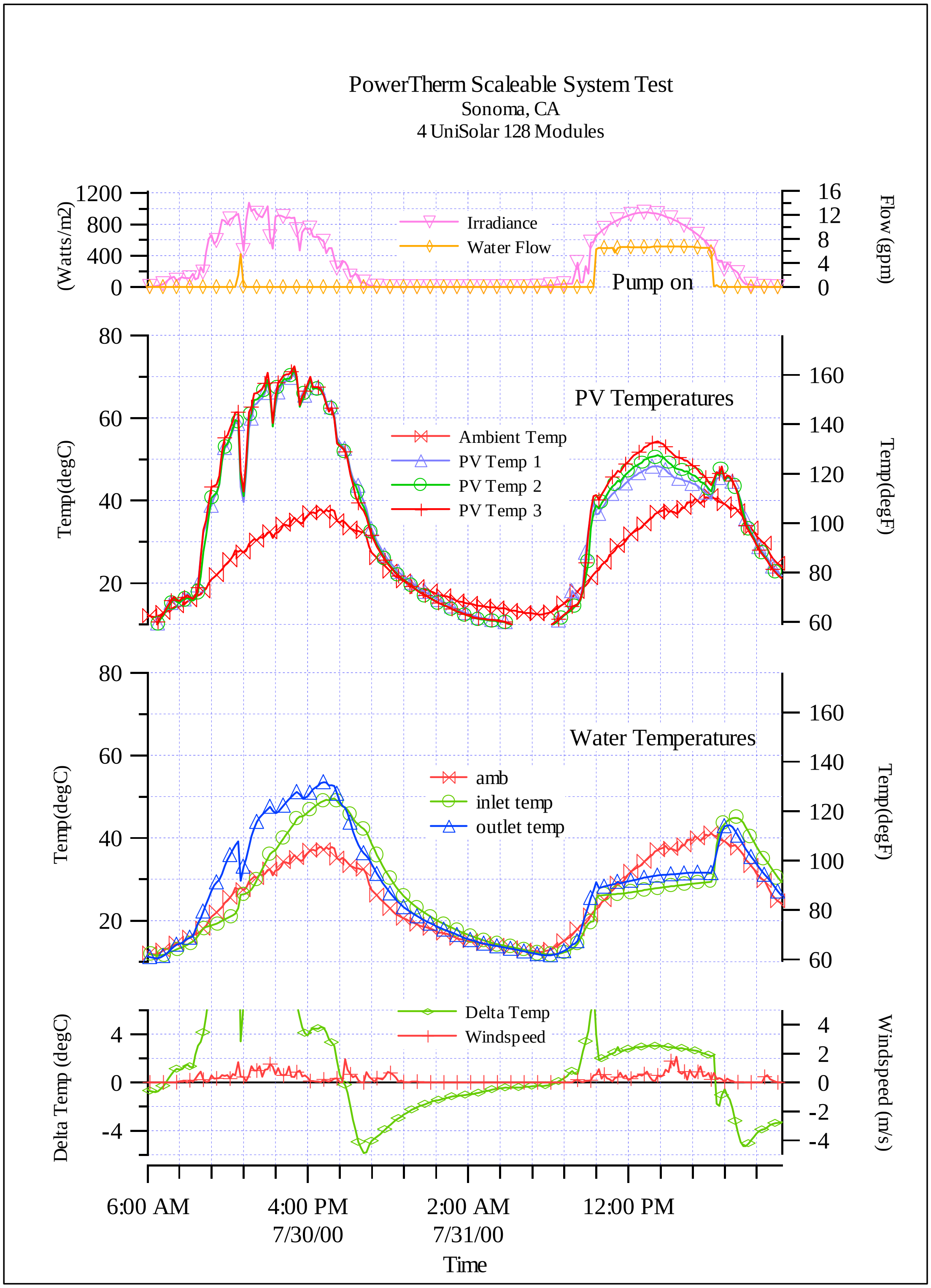

Figure 21: Sonoma, CA. PowerRoll Temperature Plot. July 30-31, 2000.

When the pool filter pump turns on (10am July 31st), the water starts removing heat from the array. PowerTherm temperatures immediately drop and maintain approximately 20°C above ambient compared to 40°C above ambient on July 30th. Outlet temperatures approach PV temperatures when flow is zero on July 30th and July 31st because the outlet temperature RTD is placed near the collectors. Testing has shown that adding a second glazing with an air gap to this collector would elevate the stagnation temperature approximately 30° C and reduce PV output 15% under these conditions.

2.6.1.2. Demonstration System – PowerTherm Final Design

A demonstration PowerTherm system of 4 collectors was installed in Sonoma, CA (Figure 22, Figure 23, and Figure 24) in March 2002. This system consisted of collectors arranged in two rows of two, with each row plumbed in series. This embodies the final PowerTherm design.

Figure 22. Final Demonstration System

Figure 23. Installation site of final demonstration system

Figure 24. System plumbing

2.6.1.3. Evaluation of Thermal Performance

The original PowerTherm prototype, based on a 1.1 m^2 PowerGuard tile, was installed for monitoring at the Western Area Power Authority (WAPA) in September of 1999. This system's performance serves as the baseline for thermal efficiency improvement goals.

Another prototype system was installed at a residence in Sonoma, CA; it has operated from April 2000 to the present. The final demonstration system was installed in March 2002 in Sonoma, CA.

Thermal performance was characterized by plotting thermal efficiency against the difference between entering water temperature and air temperature, divided by irradiance [$(T_i-T_a)/Irr$]. A plot of these data points yields a linear curve fit that characterizes the performance of solar thermal collectors under standardized conditions. The intercept value, FRλα, gives the efficiency when air and water temperatures are equal. The slope of the line, FRUL, is related to the thermal losses of the collector. A larger absolute value FRUL (steeper slope) indicates higher thermal losses. The thermal performance of the three systems is shown in Figures Figure 25Figure 26, andFigure 27.

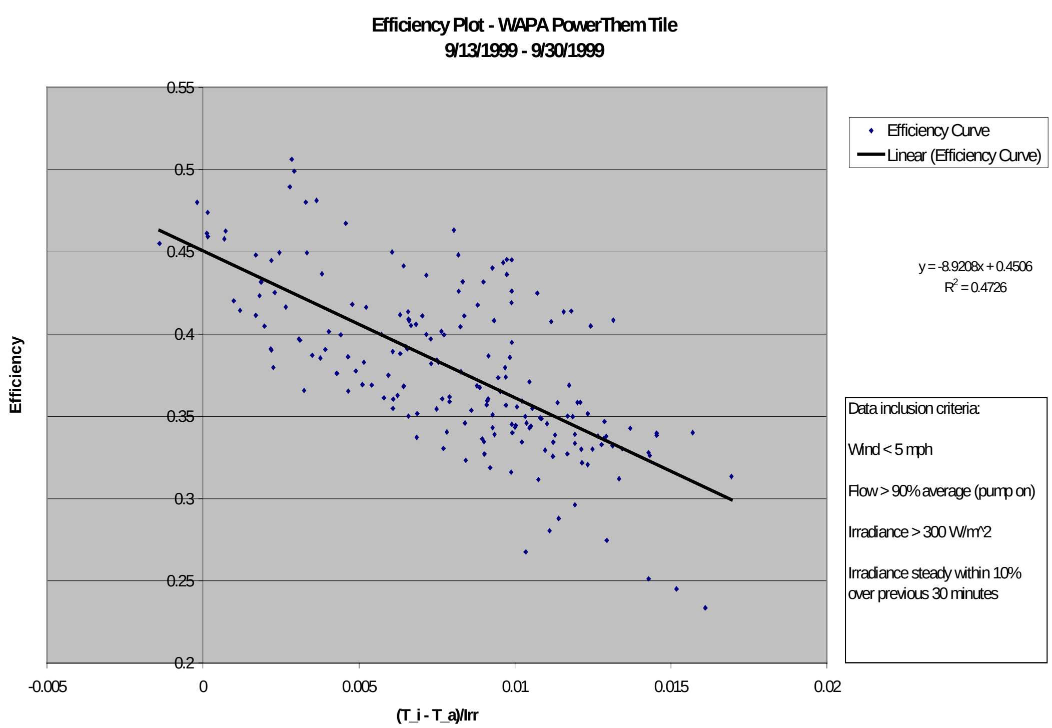

Figure 25. Thermal performance for WAPA system

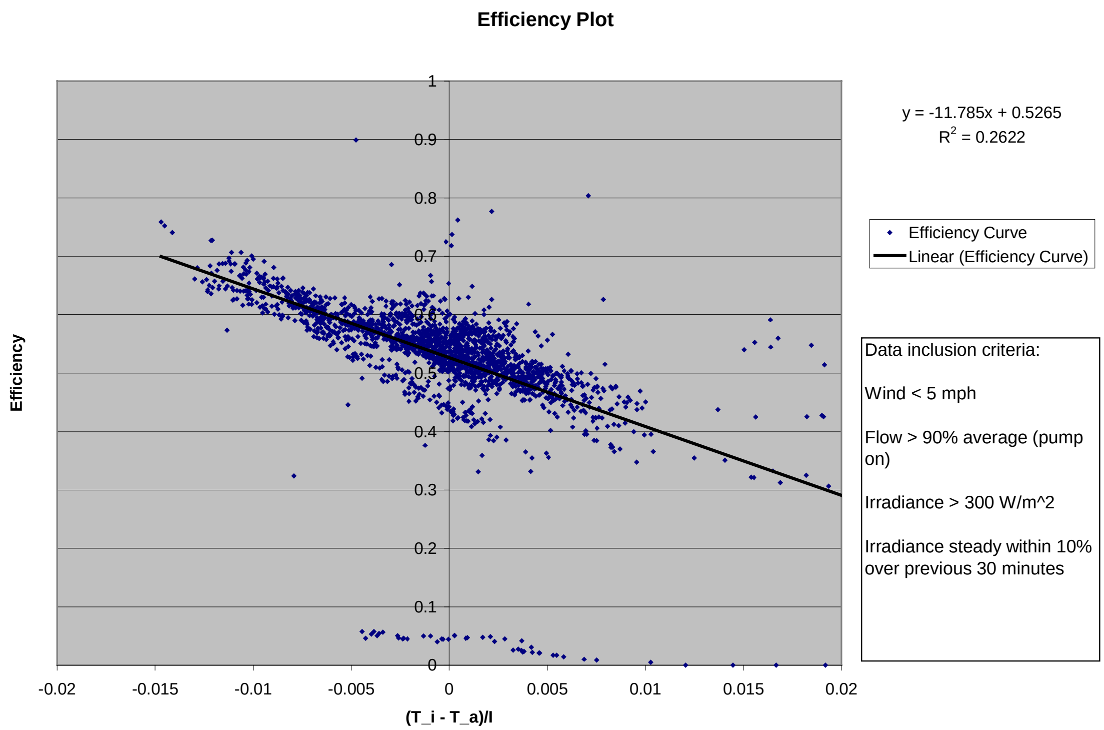

Figure 26. Thermal performance for PowerRoll system

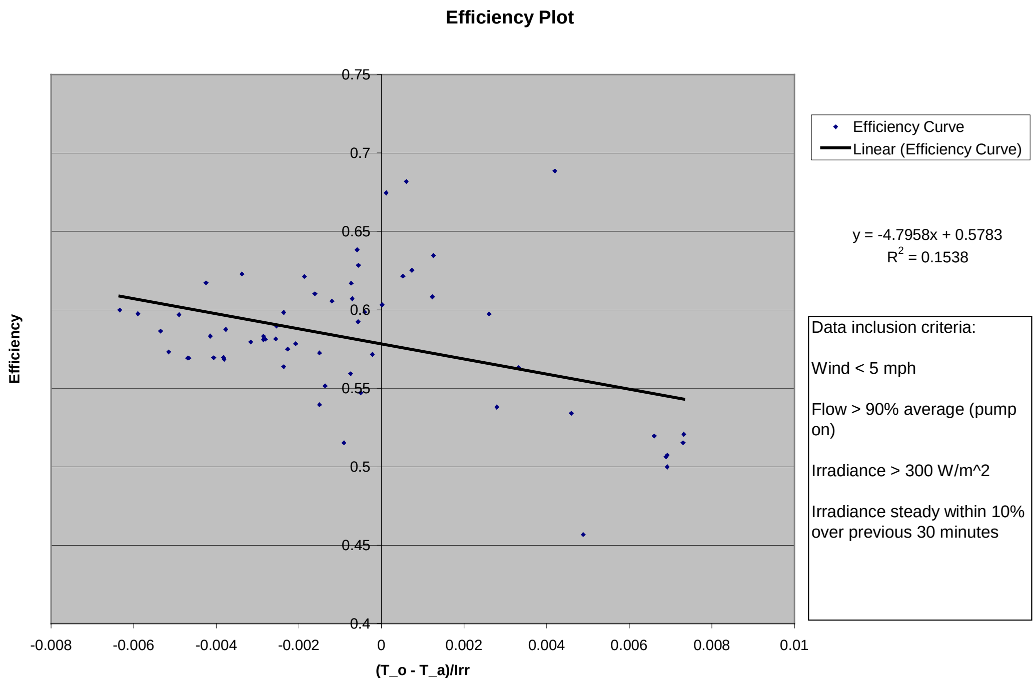

Figure 27. Thermal performance for PowerTherm demonstration system

To reiterate, the plots show a clear improvement in performance. The WAPA system had a thermal efficiency of 45%, while the PowerRoll prototype had a thermal efficiency of 53%.

Finally, the laminated PowerTherm collector exhibited an efficiency of 58%. In other words, the thermal performance of PowerTherm has been improved by 29% over the baseline system and 9% over the PowerRoll system.

2.7. Certifications

2.7.1. UL Certification

PowerLight conducted an initial Underwriters Laboratories (UL) design review of PowerTherm. This review resulted in product improvements that were incorporated into the overall product design. A list of required tests was generated for future product UL testing and certifications.

2.7.2. ICBO Certification

At the beginning of this project, PowerLight sought to obtain International Conference of Building Officials (ICBO) Certification of PowerTherm in order to allow system designers to treat this product as a reduction in live load, as an alternative to establishing an additional dead load capability to the rooftop. If allowed by ICBO, this structural design approach would have eliminated the need for a structural engineer during the design and permitting stage of PowerTherm systems.

Through investigation of ICBO evaluations of other solar thermal products, PowerLight determined that ICBO evaluation and certification were not necessary at this juncture in the development process. Among the competitors reviewed, no companies had completed an evaluation by ICBO. Furthermore, representatives of ICBO indicated that there is no precedent for ICBO evaluation of a solar thermal product.

2.7.3. International Certifications

PowerLight also researched certifications in international markets for PowerTherm, specifically IEC standards. Further market research led PowerLight to decide not to pursue international certifications. PowerLight weighed the testing requirements and cost of testing against the overall product design and potential market application/location. Based on limited international demand for this product, PowerLight chose to focus efforts on domestic product development.

2.8. Market Development

Throughout this project PowerLight, explored, identified, and developed viable markets for the successful launch of PowerTherm. This work involved potential market research outside of the U.S. PowerLight also developed a business and marketing plan to develop a strategic road map for commercialization. PowerLight trained network partners (sellers and installers) in the operation and technical aspects of this product and developed a finance package to facilitate market entry.

2.8.1. Advanced Market Analysis

To determine the feasibility of selling PowerTherm outside the U.S., PowerLight commissioned a study of the Caribbean region including parts of South and Central America; PowerLight staff also attended a PV/T conference in Amersfoort, Netherlands, to connect with the European market.

The marketing study of the Caribbean region showed that the most attractive countries in that region are where electric rates are as high as $0.24/kWh with no demand charge. The grid is often knocked out during hurricanes or the grid is often turned off as a safety precaution, so even a mild storm will effectively knock out a customer's power in this region. Customers also suffer many outages for reasons other than storms, with some countries experiencing daily blackouts. Though these factors make the Caribbean a potential market for PowerTherm, at this time there are no government incentives to install PV, and thus installation of this hybrid system is not economically viable.

The Amersfoort conference showed that the main thrust of current PV/T work in Europe is targeted at medium to high temperature DHW heating. Energy rates are much higher than in the U.S., making DHW and PV more viable products in general. Yet for a number of technical reasons, discussed earlier in this report, PowerLight continues to believe that medium to high temperature DHW PV/T is not the best initial target application for this product. Furthermore, residential pools are much less popular in Europe than in the United States, reducing the potential market size.

Clearly, the Caribbean region has great potential, as does Europe due to high-energy prices and green subsidies. However, PowerLight has chosen to focus marketing efforts on California and Hawaii due to the rebate programs and accessibility of these markets.

2.8.2. Marketing network

If commercialized, PowerTherm would be offered to the residential market through established solar contractors with expertise in both pool heating and PV. PowerLight has developed a contractor network for PowerGuard, the company's flagship roofing tile; and this network will serve for new products. PowerLight currently has certified contractors in Hawaii, California, Arizona, Michigan, Ohio, New York, New Jersey, Massachusetts, Virginia, and Rhode Island, with other states being added as new projects come in.

PowerLight would also be able to leverage its successful VAR (value-added reseller) program, developed for PowerGuard to sell and oversee product installation, to market PowerTherm.

During this project, PowerLight created a Qualified VAR Training Program, Installation Manual, and Operations and Maintenance Manual.

Commercial market penetration would likely be primarily through cross-selling PowerTherm with other PowerLight products. For example, PowerLight already has solid ties to the resort industry in Hawaii and California.

2.8.3. Finance Packaging

Through PowerLight's finance packages, customers would be able to acquire a PowerTherm system by buying it outright, taking out a loan, or through a lease. The right choice depends on a number of factors including the customer's cash and tax position, available monetary and tax incentives, and finance options available to customers based on their credit rating and their ability to take on debt. Benefits will vary by customers, depending on the particular tax situation and building construction.

3.0 Project Outcomes

3.1. Technical Objectives

The overall objective of this project was to develop a hybrid PV/T roofing product that would increase the economic value of a PV roof-tile. By integrating a solar thermal collector with a PV array, owners receive the added benefit of producing heat with little added installation and maintenance costs. The specific technical objectives were to:

- Improve heat transfer between the PV laminate and solar-thermal absorber by 40%;
- Increase the effective irradiance of the sloped collector by 5%;
- Increase the thermal performance of the overall system by 35%;
- Improve the overall system efficiency by 45%.

PowerTherm, as designed, meets the objectives of this project. Over the course of this project – and numerous design iterations – PowerLight designed and tested numerous product concepts, modifying components and manufacturing techniques, to improve overall system efficiency. Each objective is discussed in turn.

Objective #1: Improve heat transfer between the PV laminate and solar-thermal absorber by 40%.

The final PowerTherm design exhibited an overall thermal efficiency of 58%, which improved heat transfer between the PV laminate and the solar-thermal collector by 29% over our initial design concept. Over the course of this project, after testing the thermal efficiency of the EPDM (ethylene propylene diene-monomer) absorber alone, we discovered that this is a significant improvement considering that 62% is the maximum possible increase over the initial prototype. While other absorber materials such as ethylene-propylene co-polymer could provide slightly higher efficiencies, the low surface energy of the materials makes bonding PV to them almost impossible. EPDM was the best compromise of efficiency and manufacturability.

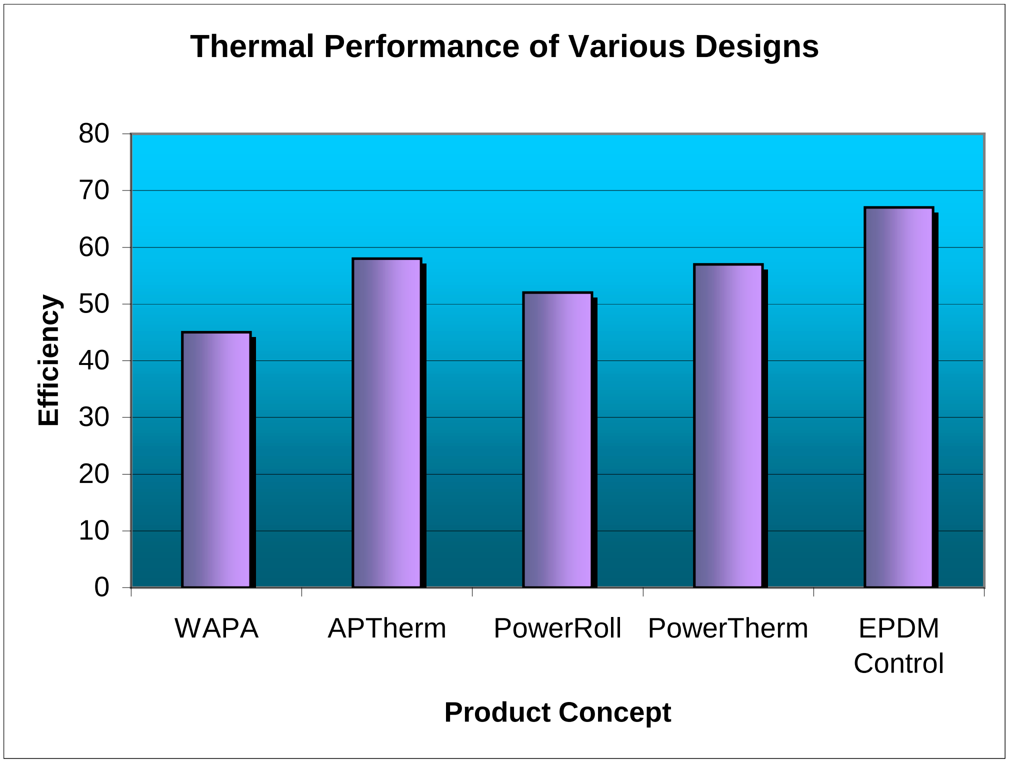

Figure 28: Graph of thermal efficiency for various design concepts

The first PowerTherm prototype was installed at the Western Area Power Administration facility in Elverta, CA (WAPA). This system performed at 45% thermal efficiency, and was used as the baseline for future prototypes. Figure 28 shows how various design iterations, for subsequent systems, improved on this first system. NOTE: for comparison, the last element of the graph shows the maximum possible thermal performance for the EPDM absorber without a PV laminate, which is 68%.

- **System #1**: WAPA (Elverta, CA) – 45% efficiency (baseline data)

WAPA: Initial product concept prototype. PowerGuard tile with ethylene-propylene co-polymer solar thermal absorber adhered to a polycrystalline PV module (Figure 29).

Figure 29: WAPA prototype: initial PowerTherm concept

- **System #2**: APTherm (Sonoma, CA) – 59% efficiency

APTherm: Incorporated EPDM solar thermal absorber. Improved performance due to improved design and components; the conductivity of the glass improved heat transfer across the collector to the water tubes (Figure 30).

Figure 30: APTherm system prototype

- **System #3**: PowerRoll (Sonoma, CA) – 53% efficiency

PowerRoll: Flexible thin film PV was adhered to an EPDM solar thermal collector with a thick layer of adhesive. This system marked the critical shift from crystalline PV to flexible thin film technology, which is much less expensive, and provided a better match in array size. The area needed for electricity generation was now similar to that needed for thermal generation. The important technical advantage of the new design is that it uses standard product sizes for both the solar thermal collector and PV laminate (Figure 31).

Figure 31: PowerRoll system prototype

- **System #4**: PowerTherm (Sonoma, CA) – 58% efficiency

PowerTherm: The final design iteration focused on promoting thermal transfer by reducing the bonding layer thickness between the EPDM and the PV laminate by 80% (Figure 32). This accomplishment required working closely with experts in bonding polymer development. In addition, manufacturing equipment and tools were developed to create a thin, high quality bond.

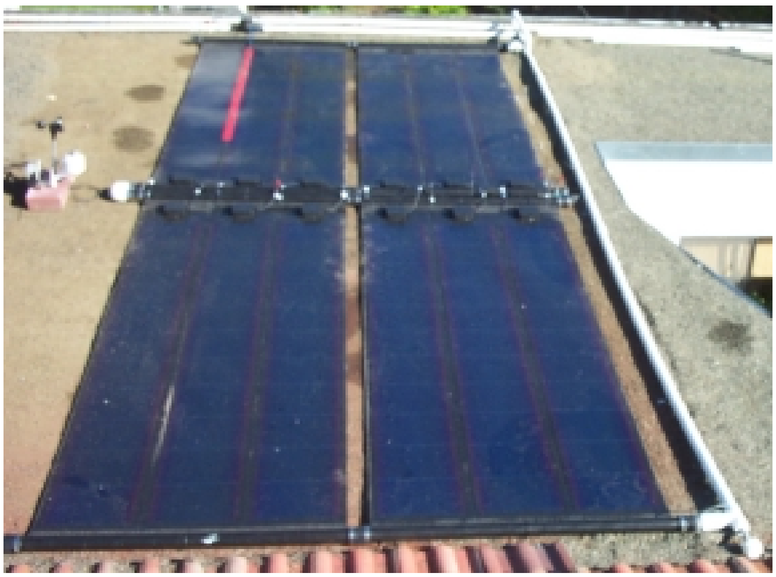

Figure 32: Final PowerTherm concept demonstration

Objective #2: Increase the effective irradiance of the sloped collector by 5%.

During the initial development stages, PowerLight found that sloping the collectors was unnecessary because the majority of residential roofs (where most of these systems will be installed) are already sloped. It is technically possible to orient the collectors at a higher angle and get as much as 15% more heat output on an annual average. However, it was not economical to add additional structure to increase the collector angle of inclination because the collector is heating swimming pools when the sun is at its zenith. If the collectors are applied in a year round application such as hot water heating and the roof is flat, the added costs and complication to slope the collectors are still more than the value of the additional heat output. Therefore, we concluded the best product is a flexible collector mechanically attached or adhered directly to the roof.

Objective #3: Increase the thermal performance of the overall system by 35%.

PowerTherm in its present form is an unglazed thermal system with no thermal storage and short piping runs. Therefore, the thermal performance for the overall system is tied most directly to the efficiency of heat transfer between the PV module and the thermal collector. The final design iteration of this product exhibited a 58% thermal efficiency, a 38% increase in overall thermal performance over the baseline design.

Objective #4: Improve the overall system efficiency by 45%

By integrating solar thermal and photovoltaic materials into one unit, overall system efficiency is greatly enhanced. Two separate systems of 500 square feet each would receive 93 kW of incident solar energy at 1000 watts/sq. meter of insolation. These two systems would yield 31 kW of thermal power, and 2.3 kW of electrical power, yielding a total system efficiency of 36%. The PV/thermal collector would have half the surface area and therefore receive only 46.5 kW of insolation, yet still produce 27 kW of thermal power, and 2.3 kW of electrical power, for a total system efficiency of 63%. Therefore, by integrating the thermal absorber into a PV laminate, the overall system efficiency is boosted by 98%.

An additional design goal of the project was to improve the PV cell efficiency by reducing operating temperature. While cell operating temperatures were reduced by contact with the thermal absorber, cell temperatures were not reduced by more than 25 ^{o} C during peak conditions. Figure 27 shows a typical summer day. On July 30th, the PV operated alone, and on July 31st, both systems were operating. From these graphs it can been seen that the cooling of the cells will translate into approximately a 5% increase in PV power at noon. While a 5% boost is significant, this does not provide significant additional annual energy production, because throughout the winter months, and during all off peak sun hours in the morning and afternoon the effect is greatly diminished, and a PowerTherm system versus PV alone would have very comparable power output during those periods.

The final PowerTherm product has the following system performance:

Table 2. Energy Performance

Energy Performance		
Assumed Solar Flux	1000	W/m^2
Collector length	10	Ft
Collector width	3.9	Ft
Collector area	39.1	Ft^2
	3.63	m^2
Energy into Collector	3629	W
Thermal Efficiency	58%	
Peak Thermal Power	2104	W
	7182	Btu/h
Peak Electric Power	192	W
	655	Btu/h
Total Peak Power	2,296	W
	7,834	Btu/h

3.2. Economic Objectives

PowerLight successfully met both economic objectives of the project. Through careful study of potential PV/T market opportunities and analysis of PowerTherm's capabilities, PowerLight identified appropriate target markets for the product as well as product elements to best serve those markets. The economic objectives for this project were to:

- Integrate thermal components into the PV assembly for less than $6 per square foot;
- Achieve a thermal component payback of less than 5 years in potential target markets.

Through extensive research and work with various manufacturing partners, PowerLight was able to meet the first economic objective of this project. The production cost (includes material and labor) for a PowerTherm tile is 6% less per square foot than our target objective (which excludes the PV and electrical components).

Once on site, the system cost increases with the balance of system components (such as plumbing, controls, installation hardware) and installation labor costs. For standard system sizes, the installed balance of system cost adds to the tile production cost. Figure 7 shows this relationship. Balance of system cost goes down because fixed costs are amortized over a bigger system, and installation labor is more efficiently used in larger installations. The total installed cost for the thermal components of this system, that is the total installed system cost excluding PV and electrical components, is the tile production cost plus the installed balance of system cost (Figure 33).

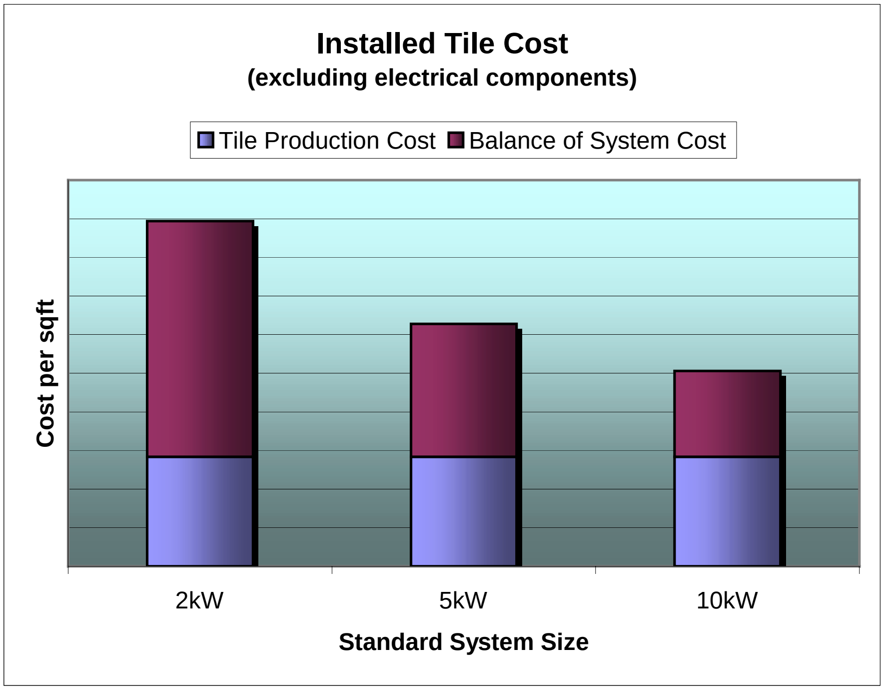

Figure 33: Graph of installed tile cost for standard size systems

In the target markets of California and Hawaii, pool-heating systems cost an average $1.50 to $5 per square foot per year, depending on usage and fuel type. Assuming that a household spends $5/sqft-yr, each standard PowerTherm system has a 4 year (2kW), 3 year (5kW), and 2 year (10kW) payback for the thermal components. This current design meets the economic goals of this product.

Choice of Target Markets

Through extensive market analysis and thorough assessment of product capabilities, PowerLight has determined that pool-heating applications, both commercial and residential, are the most viable near-term market for PowerTherm. U.S. manufacturers sold seven million square feet of pool collectors in 1994, and the market continues to expand, with more than 300,000 pool systems installed in the U.S. (data from the Solar Energy Industry Association).

Unglazed thermal collectors continue to be the best PV/Thermal collector for this market. Low stagnation temperatures will not damage the PV materials, nor accelerate encapsulant degradation, and there is a very good match between the area needed for pool heating and the area needed for electricity generation for an American or European household. Furthermore, a polymer absorber will not damage the polyethylene based EVA encapsulant, as a copper absorber will, due to copper ion exchange into the plastic.

Domestic Hot Water (DHW) pre-heating for hotels, laundries, and restaurants is still an attractive market but one to be pursued after a successful launch in the pool heating market. Other PV/T systems focus on DHW heating for residential applications; however, a typical house needs a maximum of only 40 square feet of DHW collector, which is not enough area to meet the customer's electrical load. The customer must then cover additional roof area with PV material to satisfy electrical needs, integrating two different PV systems with different operating characteristics into the household electric system. PowerLight's analysis shows that PV/T DHW systems for residential applications would not meet the economic objectives of the current project. Standard DHW systems install for approximately $65/sf of collector surface, indicating that each square foot of collector would have to generate $13/sf per year to meet the payback criteria of this contract. Currently this is not economically feasible.

Hot water is needed for hotels and other commercial loads throughout the world, and an unglazed collector serves these loads more cost effectively than glazed medium temperature collectors because of lower first cost and better performance at low inlet temperatures. The collectors might only provide 35% of the total heat requirement, however they would be more economical than glazed collectors in this application. Therefore the work done during this contract primarily focused on the design of a PV/t product for pool-heating applications.

3.3. Overall Accomplishments

The funding of this project through the California Energy Commission's PIER Program makes clear the state's commitment to making solar energy more affordable and reliable for all Californians. Through this generous contract, PowerLight demonstrated a continued commitment to adding value to solar electric systems by developing a high quality solar thermal heating system. The following is a summary of PowerLight's accomplishments during the development of PowerTherm. With PIER's help, we

- Identified lucrative target markets for PowerTherm: through extensive market analysis and a thorough assessment of product capabilities, commercial and residential pool heating applications in Hawaii and California were identified as ideal near-term markets for this product;
- Created initial product concept: by leveraging the successful product development and manufacture of PowerLight's flagship product, PowerGuard©, PowerLight quickly initiated development and testing of its first PV/T product concept;
- Developed a unique product: through design iteration, materials research, testing, and development of supplier relationships, PowerLight created a unique, high quality product which uses inexpensive flexible thin film technology bonded to commercially available unglazed solar thermal collectors. Each 4'X10' collector will produce approximately 315 kWh of electricity and 2100 kWh of heat annually for swimming pools in a California climate;
- Developed advanced manufacturing and fabrication techniques: improvements in the manufacturing process were made by reducing both cost and cycle time. Design and development of unique lamination equipment and materials led to significant progress toward product commercialization;

- Deployed six successful demonstration systems: these systems were installed and monitored at two sites in California and one in Hawaii for testing and performance verification purposes;
- Researched applicable certifications needed for commercialization: these included ICBO, IEC and UL certifications. UL conducted a design review of PowerTherm;
- Developed business and marketing strategies: PowerLight developed a finance packaging plan, identified and built alliances with key industry partners, and developed installation, operation, and maintenance plans for the product;
- Developed equipment that can be used both for production and further research;
- Optimized critical manufacturing process parameters: through iterative testing and trial manufacturing runs, these parameters were adjusted in order to achieve high quality product parts;
- Produced full-sized prototypes for certification and field-testing purposes: demonstration systems were installed to monitor performance and reliability. In addition, a full sized system has been sent to FSEC for evaluation.

4.0 Conclusions and Recommendations

4.1. Commercialization Potential

Through this project, PowerLight has progressed significantly toward commercialization of PowerTherm. The equipment developed can be used for both production and further research. This equipment has also provided valuable insight into the capabilities required of any new equipment developed in future. Optimal lamination parameters have been identified and high quality laminations achieved. Full-sized prototypes have been produced for certification and field-testing.

While technical and economic goals for this project were achieved, at this time, PowerLight has decided not to manufacture this product. Further improvements in the manufacturing process are required before moving forward. These improvements will address the following issues:

- PV de-lamination – to improve product quality;
- Manufacturing cost – to reduce production cost and cycle time;
- Product reliability – to ensure bond strength over time.

Although this continued development is beyond the scope of the PIER contract, these additional steps, discussed below, will bring PowerTherm closer to commercialization.

4.2. Recommendations

This section outlines steps that will move PowerTherm towards full commercialization. These steps address current barriers identified by PowerLight during the course of this project.

4.2.1. PV de-lamination

De-lamination has remained an issue because putting a laminated product through another lamination cycle is inherently problematic. PowerLight recognized this problem in the early stages of product development. However, assembling PV laminates from raw cells was beyond the scope of this project due to the tooling and assembly expertise required.

The next step is for PowerLight to work more closely with the selected PV laminate manufacturer to produce a specialized manufacturing unit in which the solar thermal collector material, EPDM, is substituted for the manufacturer's standard back skin material during their lamination process. The dual lamination process in the manufacture of PowerTherm would thus be simplified to a single lamination operation, which should entirely eliminate the de-lamination issue. This development path could lead to the licensing of PowerTherm technology to the PV laminate manufacturer, which could produce it in parallel with their other products at their manufacturing facilities.

If this development does not materialize with the PV laminate manufacturer, an alternative path can still be pursued through a secondary lamination process. This would require more research into the causes and solutions to de-lamination. On a positive note, the research carried out during this PIER contract provides strong hints to solving these problems. In particular, reducing temperature gradients across the components will reduce the thermal stresses that contributed to the problem.

4.2.2. Manufacturing costs

Regardless of how PowerTherm is produced, cycle time must be reduced to lower the overall manufacturing cost of the product. This can be achieved by developing a manufacturing system in which the temperature gradients are more even during the lamination process. These improvements would reduce the cycle time needed to laminate one part from 90 minutes to 20 minutes (3 parts per hour).

Assuming sufficient other infrastructure and staff are available to handle this lamination rate, this would yield roughly 10,000 units per year with one lamination press operating one shift. Assuming a capital equipment cost of $50,000 for the laminator, and other capital costs of $150,000, the capital cost per unit over a one year amortization period is $20. Tooling costs are therefore very low compared to the costs of the collector components, which are approximately $1000. However, the overhead associated with the 5000 sq. ft. facility and personnel required to manufacture PowerTherm would add another $25 per collector. These costs assume that the facility instantly starts selling at maximum capacity, which is unlikely during the early stages of product release; costs per collector are thus somewhat higher.

4.2.3. Product Reliability

The issue of the PV-EPDM bond failing under thermal cycling surfaced in the final days of the contract period. This bond failure may be due to the lamination process or the bonding layer itself. Further research into the bonding process and material will be required to resolve this issue. This work will include carefully monitoring the lamination temperatures across a number of samples, and then performing freeze-thaw testing on these samples. During this investigation, PowerLight will work closely with the bonding layer manufacturer.

Additionally, the long-term reliability of the product will be assured through continued inspection of demonstration systems and accelerated life-testing results. During the continued development of PowerTherm, PowerLight will continue to pursue FSEC approval and UL listing.

4.3. Benefits to California

While further steps need to be taken to bring the PowerTherm product to full commercialization, this product offers the people of California many benefits.

PowerTherm expands the PV market by increasing the value of a PV system to prospective purchasers who have pools by providing the added benefit of pool heating with little added installation and maintenance costs. During operation, the PV/T system harnesses the abundant source of clean solar energy into both electric power and thermal energy. Californians with pools who purchase this product will benefit greatly by saving on energy costs over the life of this product while sparing the environment from harmful emissions from fossil fuel-based electricity generation. Most pool owners have been hit by a large increase in electricity bills because they are "above baseline" users. This system will remove that portion of their bill through on site generation.

PowerTherm will create manufacturing and sales jobs within California. Sales of this product will generate state tax revenue through the growth of California businesses required to manufacture, distribute, and service this product. Revenues generated through the sales of this product may one day fuel the research, development, and improvement of future alternative energy generation products.

Commercialization of PowerTherm will increase the market and demand for hybrid solar energy systems by making them more affordable to Californians. This expansion will foster further improvements to related technologies and components that may yield an increase in the overall performance and efficiency of these systems. Such improvements will continue to drive down the cost of these alternative energy systems.

The development and deployment of additional solar electric systems, such as PowerTherm, throughout this state and the world benefit all Californians. Solar-electric power systems provide a domestic source of energy that is plentiful, sustainable, and available throughout the United States.

Alternative energy generation also provides an economic hedge against volatile fossil fuel prices. Bringing systems like PowerTherm to the general market helps alleviate the current energy generation shortage – particularly during peak demand.

Because solar electric systems are flexible and modular enough to install just about anywhere, photovoltaic technology provides a low cost on-site energy generation alternative to the end-user. On-site, distributed energy generation benefits not only the system owner but also the community at large by reducing energy losses during transmission and thus offsetting the additional cost of transmission and distribution infrastructure.

Harnessing the sun's energy for electric power and thermal energy produces no pollution-causing emissions such as nitrous oxide, or greenhouse gases such as carbon dioxide. Building an alternative energy infrastructure provides insurance against the threat of global warming and climate change.